MEASUREMENT AND CORRECTION OF LOW-BETA OPTICS AT TEVATRON

Valeri Lebedev

Contents

1. Introduction
2. Differential orbit measurements
3. Optics correction
4. Results of optics modeling
5. Extended differential orbit measurements
6. Conclusions

Run II meeting
FNAL
July 29, 2004

Introduction

Optics status

- **Injection**
  - We had emit. growth at inject. due to optics mismatch and coupling
  - Major problems are fixed
  - Improvements are desirable but hardly will bring lum. increase
- **Flat top (inj. Optics, 980 GeV)**
  - No major problems we observed
- **Low-beta**
  - Tevatron luminosity has been affected by large betas at IP
    - Suspicions came from dif. orbit measurements
    - Assurance came from tune shift measurements for IP quads
  - Beta-functions at IPs were brought to design value of 35 cm
    - ~15% gain in luminosity
  - Further improvements are desirable
    - Beta-wave in sectors
    - Dispersion correction in IPs
    - “Local” coupling correction

Optics instrumentation

- BPMs
  - Optics measurements and correction have been complicated by
    - Poor performance of 30 years old BPM system
      - Poor BPM accuracy, ~150 μm rms resolution
      - Not functional ring wide turn-by-turn mode of BPM operation
  - New BPM system will address all problems
- Software
  - OptiM has been used for data analysis
    - Tedious and not sufficiently accurate
    - Fast measurements – long analysis
  - LOCO software is presently built in collaboration with ANL
    - Long measurements (~1 hour)
      - Fast analysis
      - Better accuracy
      - Additional knowledge

        BPM gains, rolls and incorrect positions

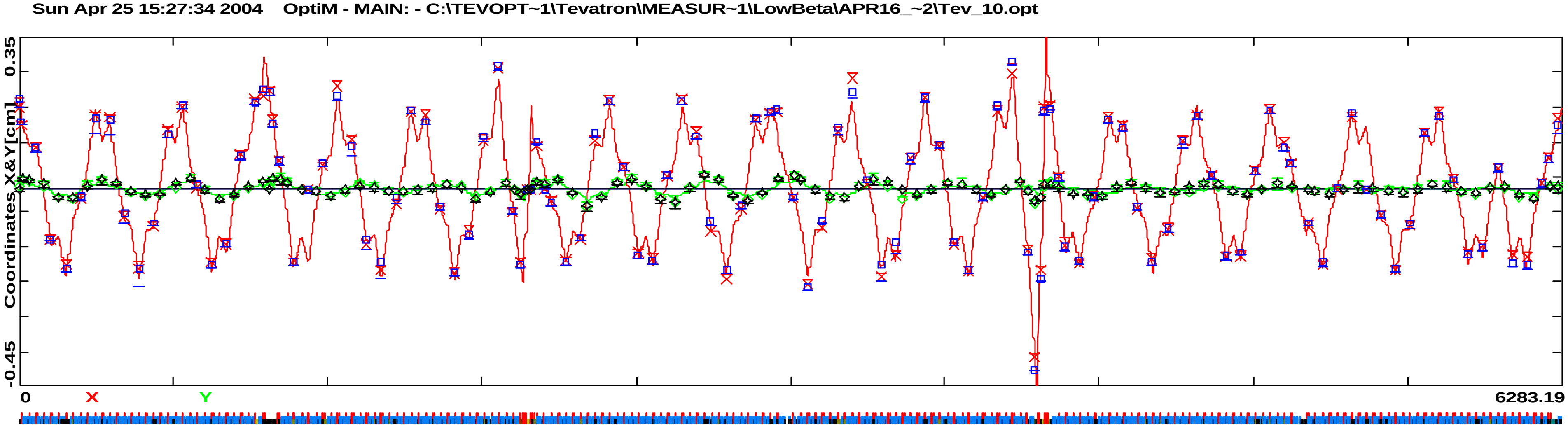
        kicker calibration

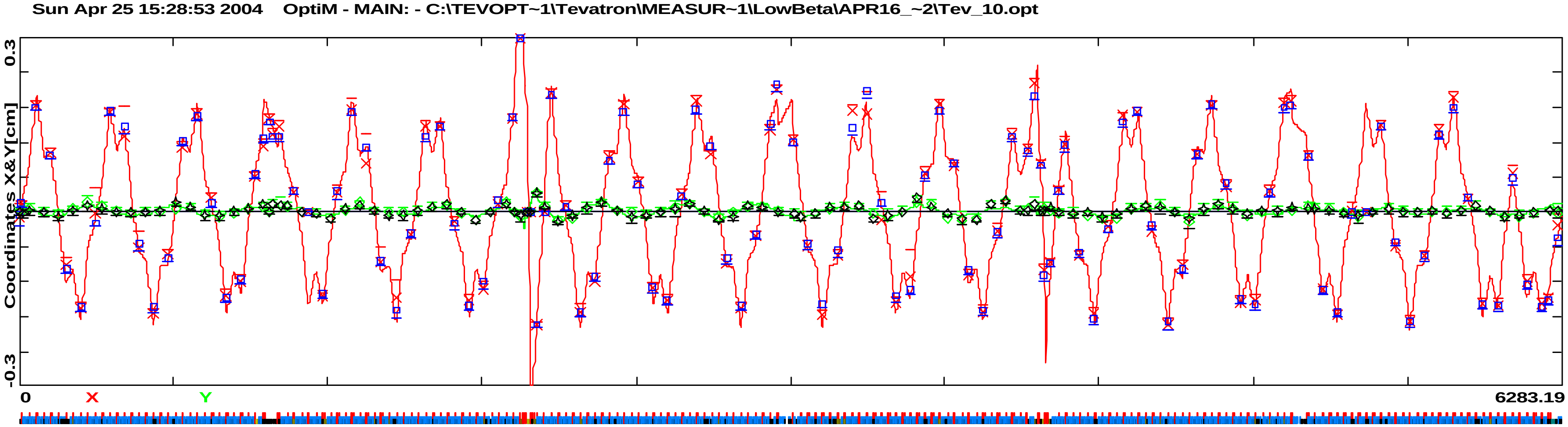
Other problems needs to be addressed

- Limited time for optics measurements and studies
- Beam motion (~ ±100 μm, 10-20 Hz) will spoil the accuracy
  - Turn-by-turn BPMs would address this problem

Differential orbit measurements

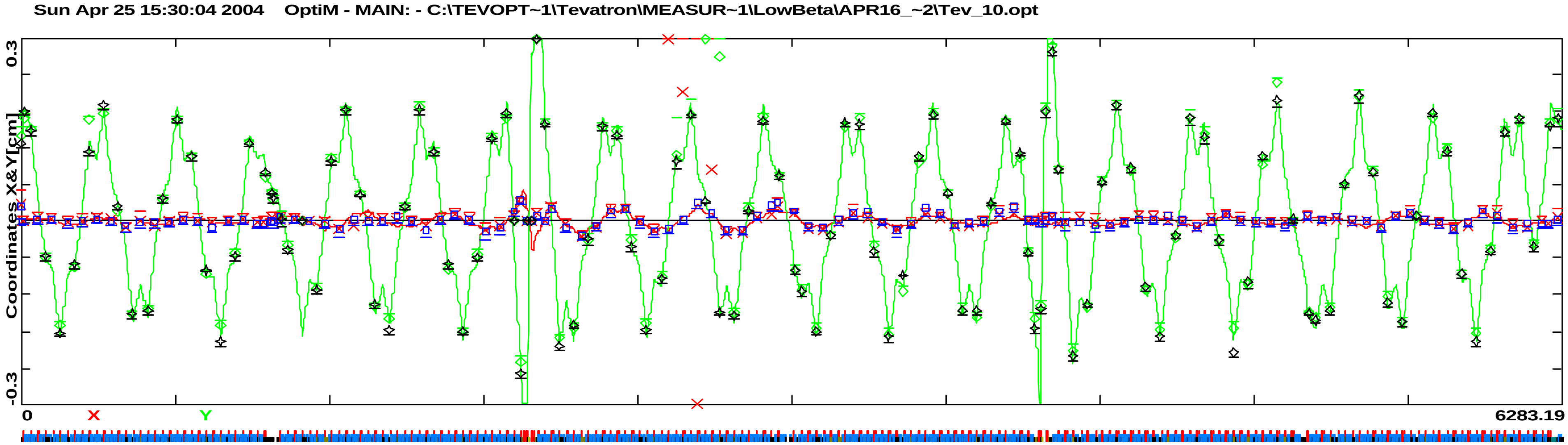
Results of April 16 measurements

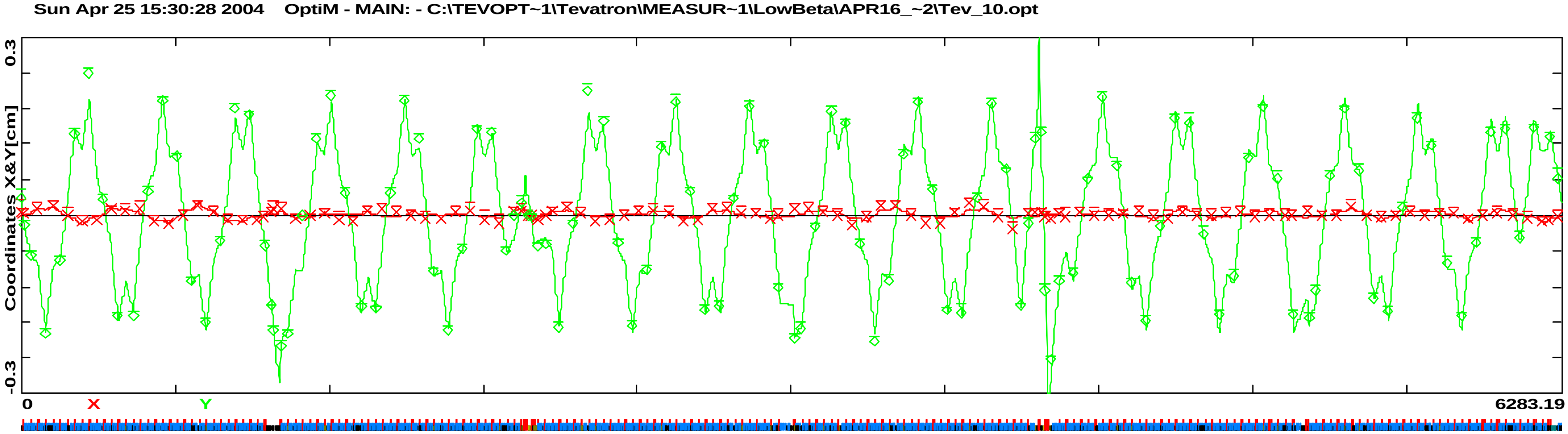




Horizontal orbits

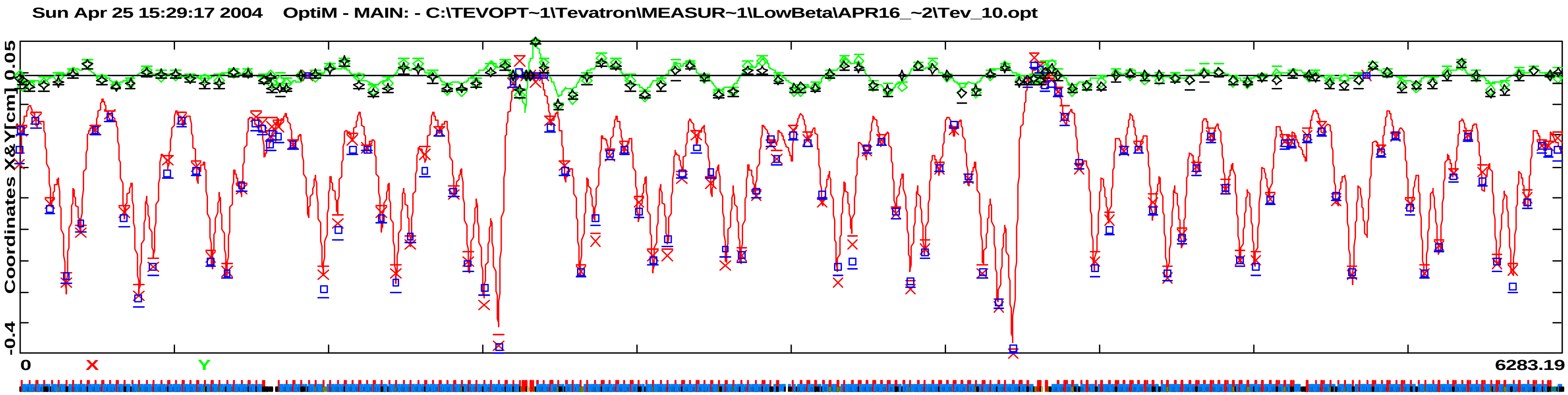
Results of April 16 measurements (continue)



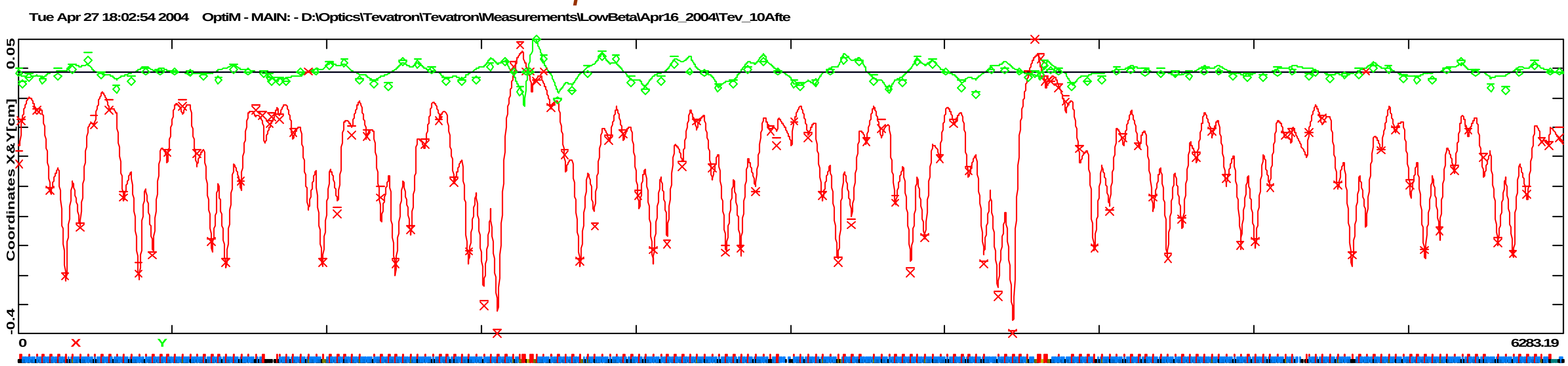


Vertical orbits

Results of April 16 measurements (continue)



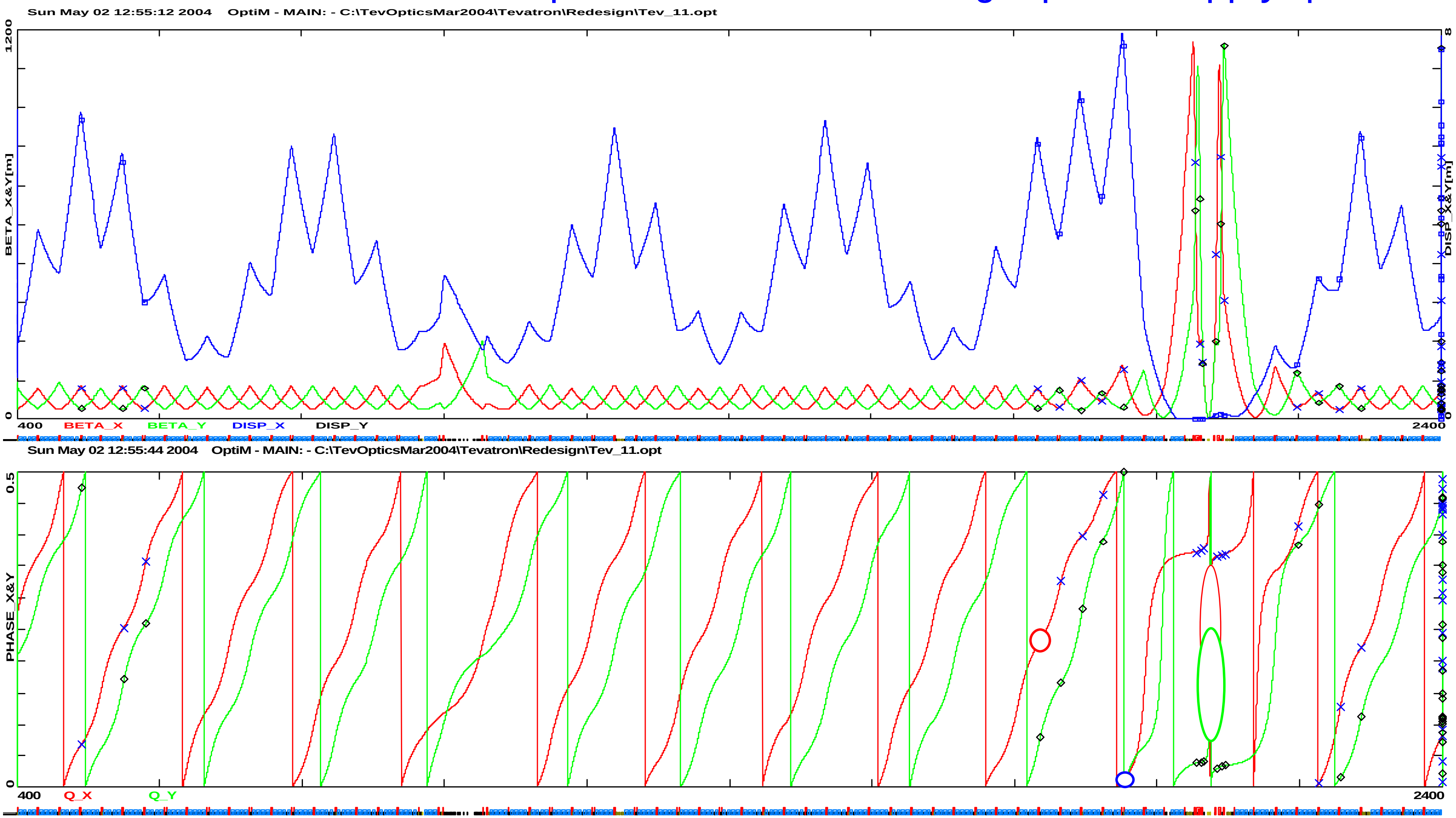
Dispersions before correction



Dispersions after correction

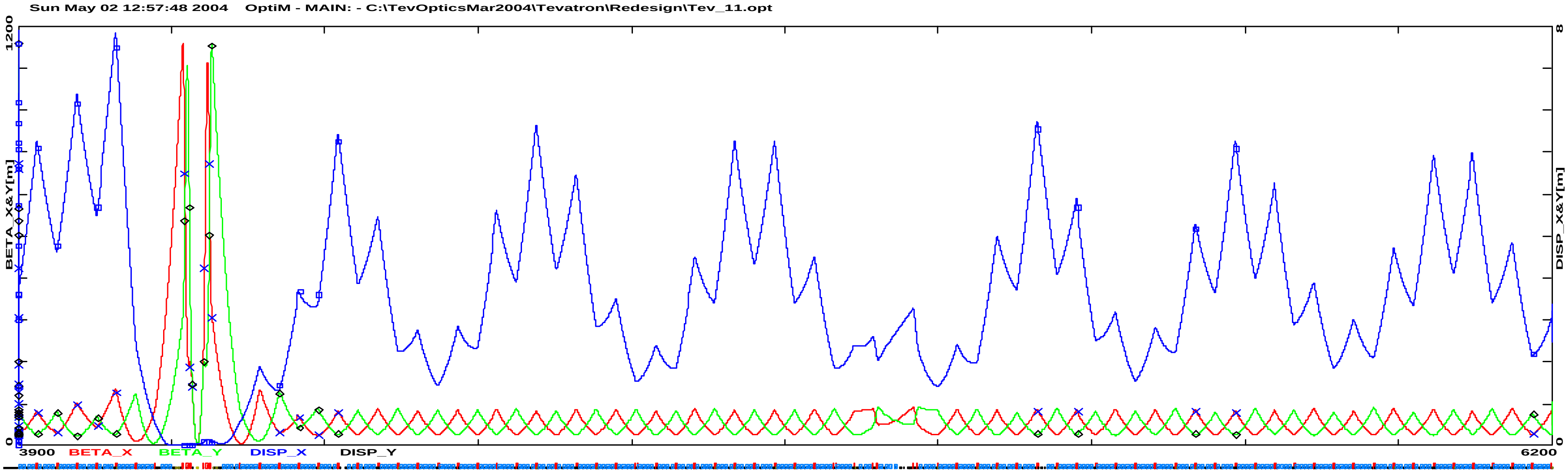
Optics correction

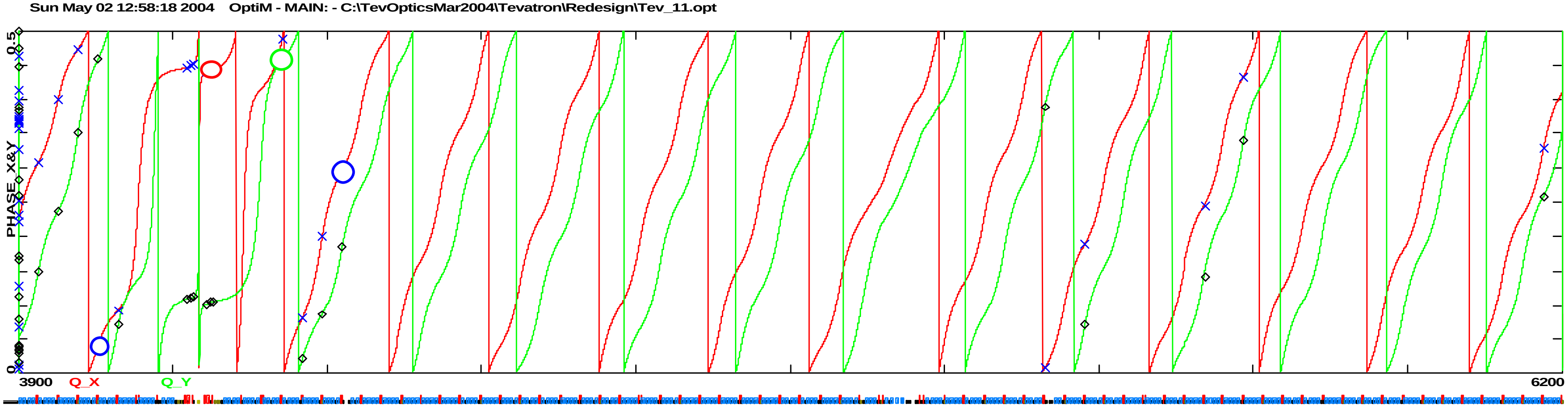
Beta-functions and betatron phase advances for single power supply quads



QF28 QF32 QF33 **QA42** AQ0 AQ9 QA45 **AQ7** B0Q2F - B0Q2D BQ7 QB15 BQ9 BQ0

Beta-functions and phase advances for single power supply quads (continue)





QC42 CQ0 CQ9 QC45 **CQ7** D0Q2F - D0Q2D **CDQ7** QD15 DQ9 **DQ0** QE17 QE19 QE26 QE28 QE47

Table 1. Present, future and design quad values for quadrupole power supplies, beam momentum 979.529 GeV/c.

Name	Design, [A]	Present, [A]	Differen-ce,P-D, [A]	Correc-tion,[A]	Final, [A]
B0 and D0 quads					
T:QA42	-44.23	-44.24	-0.01	-1	-45.23
C:AQ0	104.78	100.72	-4.06		
C:AQ9	577.41	555.56	-21.85		
T:QA45		0.00	0.00		
C:AQ7	630.53	607.44	-23.09	-5 (Disp)	602.44
C:B0Q6	3675.34	3647.38	-27.95		
C:B0QT6	-22.90	-22.90	-0.01		
C:B0Q5	1981.01	1972.50	-8.51		
C:B0Q2	4721.28	4721.76	0.47	-4.5	4717.26
C:B0QT2	-10.10	0.00	10.10		
C:B0Q3	4671.28	4666.29	-4.99	-4.5	4661.79
C:B0QT3	-6.63	3.87	10.50		
C:BQ7	703.16	680.08	-23.07		
T:QB15	-44.23	-44.24	-0.01		
C:BQ9	497.68	479.72	-17.96		
C:BQ0	51.60	49.82	-1.78		
T:QC42	-44.23	-44.24	-0.01		
C:CQ0	104.24	100.72	-3.51		
C:CQ9	572.69	555.56	-17.13		
T:QC45		0.00	0.00		
C:CQ7	630.44	607.44	-23.00	-7	600.44
C:D0Q6	3716.35	3647.38	-68.96		
C:D0QT6	-22.90	-22.90	-0.01		
C:D0Q5	1984.05	1972.50	-11.54		
C:D0Q2	4715.79	4711.07	-4.71		
C:D0QT2	-3.40	19.60	23.00		
C:D0Q3	4649.12	4636.99	-12.12		
C:D0QT3	2.06	24.06	22.00	-2.7	19.3
C:DQ7	705.40	680.08	-25.31	-46(Disp)	
T:QD15	-44.23	-44.24	-0.01		
C:DQ9	497.24	479.72	-17.53		
C:DQ0	51.78	49.82	-1.96	3.5*QA42 =-3.5	46.32
Trim quads					
T:QFA4	-12.02	-14.18	-2.16		
T:QDD1	7.62	10.50	2.88		
T:QFE1	-13.09	-14.64	-1.56		
T:QDE2	-7.56	-5.06	2.50		
T:QFF3	-6.21	-6.70	-0.49		
T:QDF4	12.41	15.38	2.97		
T:QE17	-13.09	-14.64	-1.56		
T:QE19	-22.90	-13.00	9.90		
T:QE26	0.13	-5.71	-5.84		
T:QE28	1.69	-1.22	-2.90		
T:QF28	4.07	-10.32	-14.39		
T:QF32	-18.53	-24.58	-6.05		
T:QE47	-1.31	3.71	5.02		
T:QF33	-0.58	-0.21	0.37		

Final results for optics correction

Next changes were performed to correct optics and dispersion

B0Q2 and B0Q3 were decreased by 6 A

B0Q2: from 4722 to 4716

B0Q3: from 4666 to 4660

D0QT3 was decreased by 2.7 A from 24.06 to 21.3

QA42 was changed by -2.5 A from -44.24 to 46.86

AQ7* was changed by -5 A from 607.4 to 602.6

CQ7* was changed by -7 A from 607.4 to 600.9

DQ0 was changed by -3.5 A from 49.82 to 46.28

DQ7 was changed by -25.6 A from 680 to 654.4

*AQ7 and CQ7 made minor dispersion correction in both IPs

Choice of trim quads

- Single power supply quad
- Large difference between beta-functions
- Should not excite hor. dispersion in IPs (combination of 2 quads are used)
- ~45 deg. in betatron phase

Correction and control of optics adjustments

- Accuracy of differential orbit measurement ($\Delta\beta/\beta$~15-20%) has not been sufficient to correct optics to $\Delta\beta/\beta$~5%
- Local beta-function measurements have been used for optics measurements
  - Model prediction of tune shifts for corrected model have been used as a target
  - MCAD spreadsheet was used to predict quad changes from measured tune shifts

Model prediction for tune changes

	DI [A]	Qx0	Qx	DQx	Qy0	Qy	Dqy
B0Q2	10	0.58525	0.59638	**0.0111**	0.575111	0.586104	**0.0110**
B0Q3	4	0.58525	0.595517	**0.0103**	0.575111	0.585205	**0.0101**
D0Q2	10	0.58525	0.596051	**0.0108**	0.575111	0.585972	**0.0109**
D0Q3	4	0.58525	0.595593	**0.0103**	0.575111	0.585319	**0.0102**
QE26	25	0.58525	0.593715	0.0085	0.575111	0.572406	-0.0027
QE47	25	0.58525	0.588062	0.0028	0.575111	0.566641	-0.0085
Other quads							
B0Q2T	-3	0.58525	0.590561	0.0053	0.575111	0.565547	-0.0096
B0Q3T	2	0.58525	0.593086	0.0078	0.575111	0.572375	-0.0027
D0Q2T	-3	0.58525	0.590565	0.0053	0.575111	0.565514	-0.0096
D0Q3T	2	0.58525	0.593083	0.0078	0.575111	0.572381	-0.0027

Measurements before correction (April 16, 2004)

	DI [A]	Qx0	Qx	DQx	Qy0	Qy	Dqy
B0Q2	10	0.5858	0.5944	**0.0086**	0.5772	0.5863	**0.0091**
B0Q3	5	0.5859	0.5945	**0.0086**	0.5774	0.588	**0.0106**
B0Q2T	5	0.5859	0.5786	-0.0073	0.5775	0.5892	0.0117
B0Q3T	2	0.5859	0.5913	0.0054	0.5775	0.5759	-0.0016
D0Q2	10	0.5859	0.5948	**0.0089**	0.5775	0.5868	**0.0093**
D0Q3	5	0.586	0.5953	**0.0093**	0.5776	0.5883	**0.0107**
D0Q2T	5	0.586	0.578	-0.008	0.5778	0.5897	0.0119
D0Q3T	2	0.586	0.5921	0.0061	0.5776	0.5757	-0.0019

Measurements after correction (May 22, 2004) % to model

T:QE17H[25]	20	0.5845	0.5919	0.0074	0.5709	0.5691	-0.0018	9.05	6.51
T:QE19H[25]	20	0.5845	0.5898	0.0053	0.5709	0.5687	-0.0022	-14.32	-19.50
T:QE26H[25]	20	0.5847	0.5898	0.0051	0.5709	0.569	-0.0019	-18.11	-16.67
T:QE28F	20	0.5847	0.5926	0.0079	0.5709	0.569	-0.0019	10.07	20.33
T:QF28F	20	0.5847	0.5904	0.0057	0.5709	0.5685	-0.0024	-5.11	-8.26
T:QF32F	20	0.5849	0.5921	0.0072	0.5708	0.5688	-0.002	5.16	14.29
T:QE47F	20	0.5849	0.5873	0.0024	0.5709	0.5655	-0.0054	6.24	-6.33
T:QF33F	20	0.585	0.5872	0.0022	0.5708	0.5644	-0.0064	-13.83	7.01
C:B0Q2H[25]	10	0.5849	0.5975	**0.0126**	0.5708	0.5824	**0.0116**	**-8.72**	**7.74**
C:B0Q3H[25]	5	0.585	0.5976	**0.0126**	0.5709	0.5836	**0.0127**	**-19.39**	**3.18**
C:B0QT2H[25]	5	0.585	0.5847	-0.0003	0.5711	0.5845	0.0134	-97.52	-14.83
C:B0QT3H[25]	2	0.585	0.5929	0.0079	0.5711	0.5687	-0.0024	-10.01	-8.22
C:D0Q2H[25]	10	0.585	0.5973	**0.0123**	0.5711	0.5822	**0.0111**	**1.77**	**-5.48**
C:D0Q3H[25]	5	0.5852	0.5989	**0.0137**	0.5711	0.5837	**0.0126**	**0.87**	**-7.69**
C:D0QT2H[25]	5	0.5854	0.5747	-0.0107	0.5713	0.5849	0.0136	0.93	-15.47
C:D0QT3H[25]	2	0.5852	0.5939	0.0087	0.5713	0.5685	-0.0028	7.87	-7.59

Beam aiming in IPs

- Yuri Alexahin idea for “model independent” beam aiming
  - Measure orbit response to each separator
  - Combine separators in one arc to null orbit excitation in another
  - Verify computations by measurements
- New values for separators

B11H	B17H	C49H	D11H	D48H	A49H
105	41.8	105.2	96	40.8	100.5
B11V	C17V	C49V	D11V	A17V	A49V
110	52.7	103.3	115	6.2	86.4

- Polarities are the same as before, no need to flip A17V.

Alpha bumps

- Verified that coefficient coincide with model predictions
- Verified that alpha bumps do not affect luminosity in another IP

Coefficients for alpha bumps at low beta

		Correct values for 1 cm waist displacement	Present mult (as May 5, 2004)	Scaled correct values to compare to present mult
Horizontal				
B0Q2	$kA1	-0.9	2.143	2.143
B0Q3	$kA2	-0.3798	1	0.904346
B0QT2	$kA3	1.197	-2.801	-2.85019
B0QT3	$kA4	1.071	-2.47	-2.55017
Vertical				
B0Q2	$kA6	-0.62	0.45	-1.0702
B0Q3	$kA5	-0.1922	1	-0.33176
B0QT2	$kA7	1.0416	1.818	1.797934
B0QT3	$kA8	0.9362	1.616	1.616

Results of optics modeling (S. Valishev fitting)

Global corrections

Skew Quad in dipoles = 2.17 units (1.5 times of injection value)

Main bus quad fudge factor = 0.194% (~0.05% above injection value)

Local corrections

$F_B0Q3= -1.1%

$F_B0Q2= -0.25%

$F_B0Q3D = 0.0%

$F_B0Q3F = 0.09%

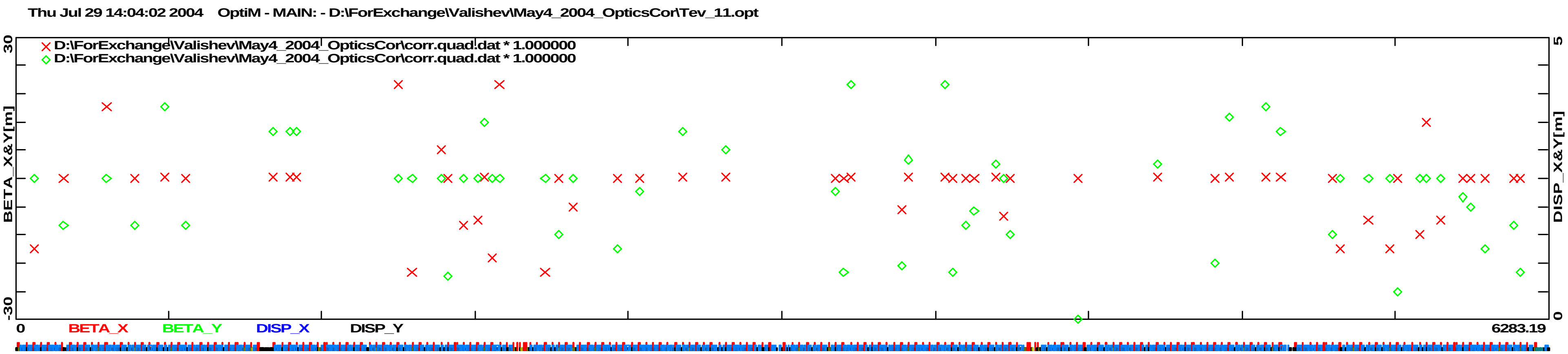
$F_D0Q3= -0.9%

$F_D0Q2= -0.25%

$F_D0Q3F= 0.05%

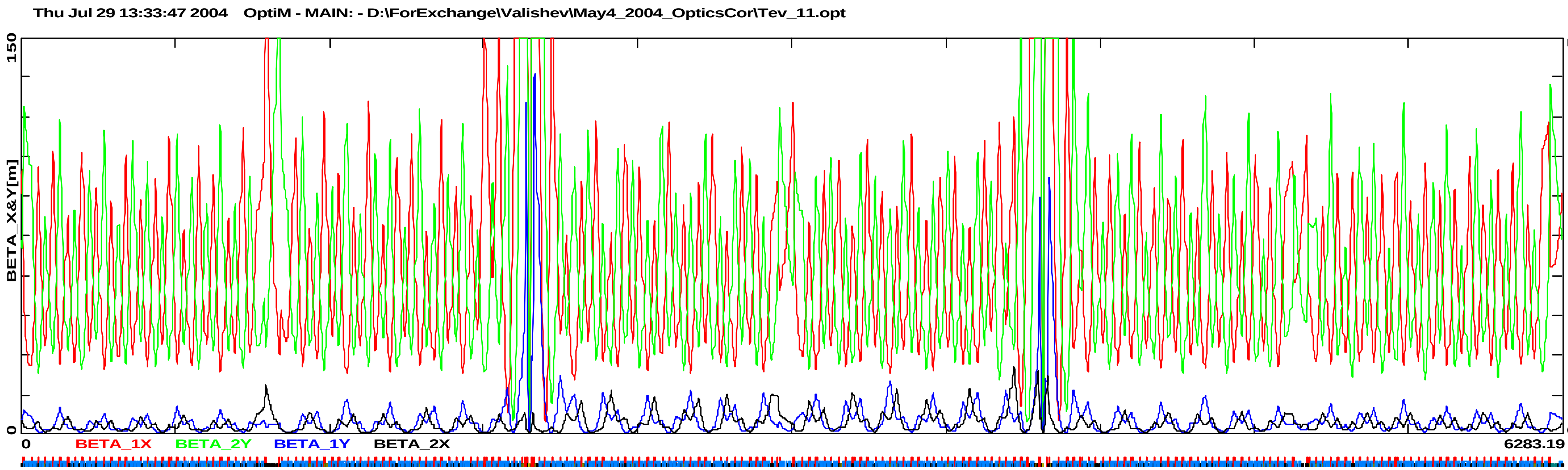
$F_D0Q3D= -0.16%

Optics deficiencies along Tevatron in kG

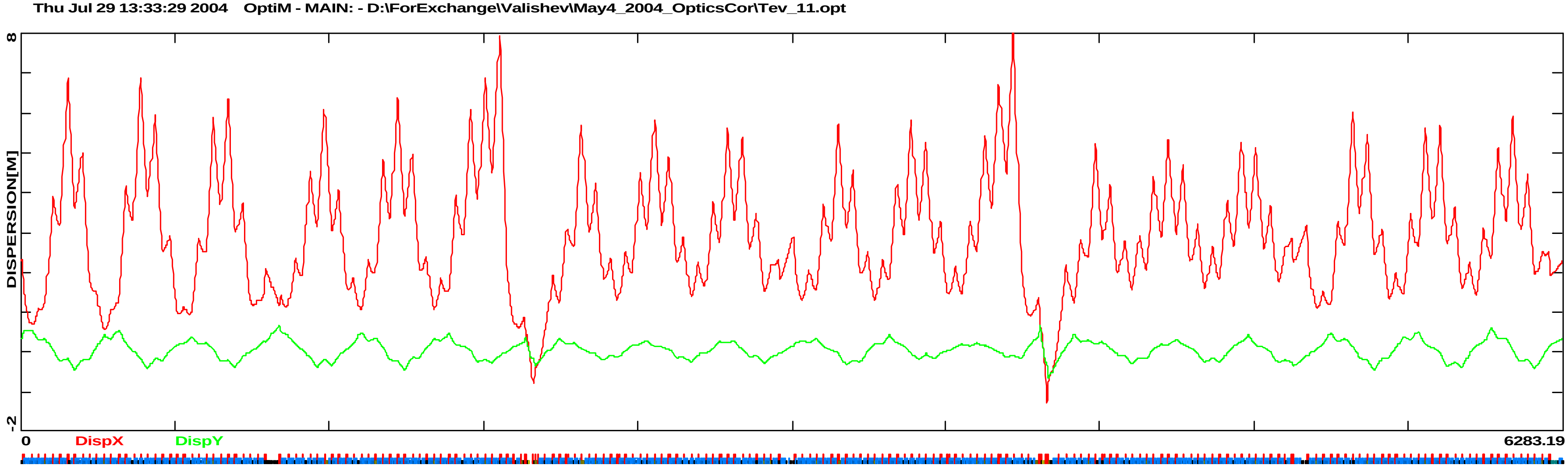


x – quad corrections, + - skew-quad corrections

skew-quad strength in one dipole = 1.12 kG



Thu Jul 29 13:33:47 2004 OptiM - MAIN: - D:\ForExchange\Valishev\May4_2004_OpticsCor\Tev_11.opt
BETA_X&Y[m]
150
0
5
0
0
6283.19
BETA_1X
BETA_2Y
BETA_1Y
BETA_2X



Thu Jul 29 13:33:29 2004 OptiM - MAIN: - D:\ForExchange\Valishev\May4_2004_OpticsCor\Tev_11.opt
DISPERSION[M]
8
-2
0
6283.19
DispX
DispY

Extended differential orbit measurements

- The data analysis of differential orbit data, additionally to optics errors, is complicated by difference in BPM response for different BPMs, their rolls, as well as by rolls of correctors and errors in their strength
- To take this into account we have used a method proposed in Ref. [1]. The effort is build as collaboration between FNAL and ANL and aimed to upgrade the software developed for APS [2]. The major requirements are its integration with FNAL data structures and optics software and the requirement to take into account X-Y coupling and both dispersions
  - We put as unknown: Quad strengths and rolls, BPM responses and rolls, correctors strength and rolls – altogether about 800 unknowns
  - To have sufficient redundancy with perform measurements with 50 correctors which yields ~10,000 equations
  - SVD is used to find unknowns from the measured data
- The first results of data analyses have been recently obtained. Further work is required to finish the project.

Response matrix fit (non-coupled case) at Low Beta optics

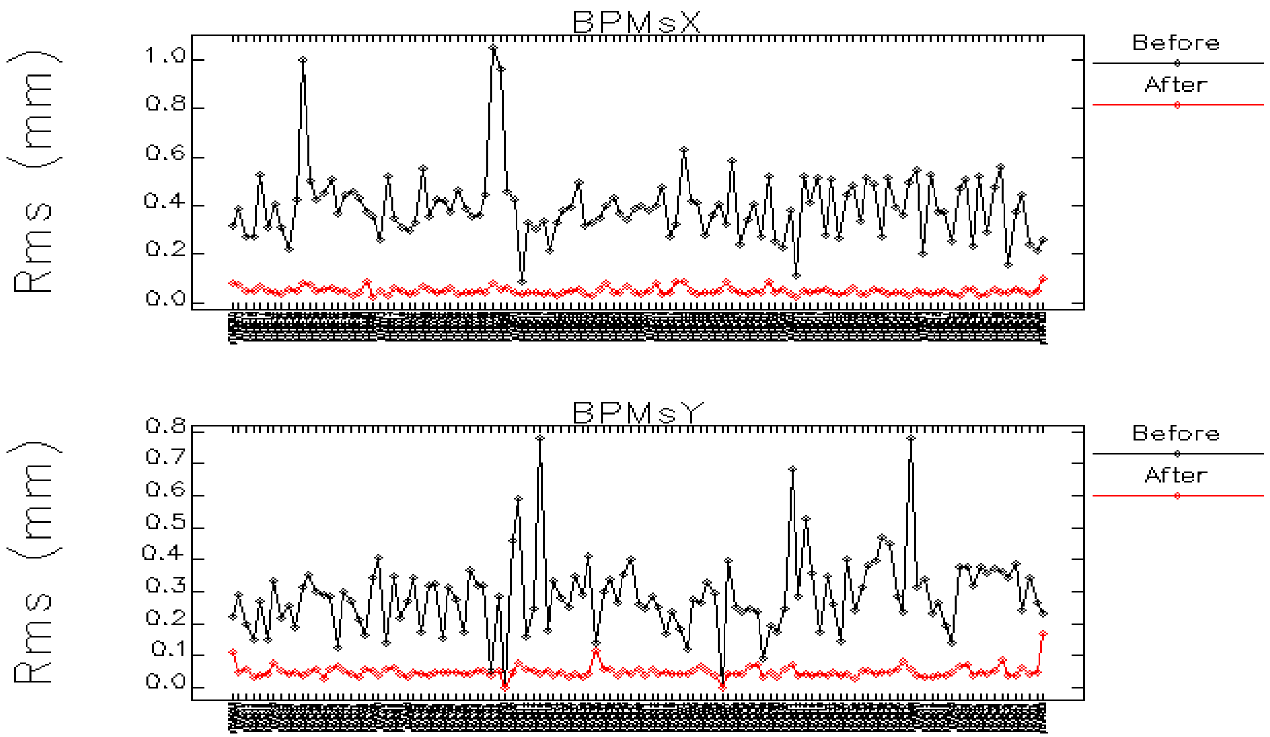
Number of variables: 503

Number of measurements (equations): 6291

Rms difference between measured and calculated response matrix:

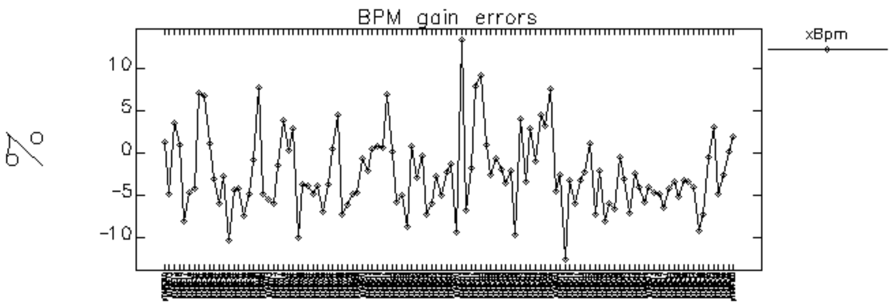
Before the fit: 370 μm

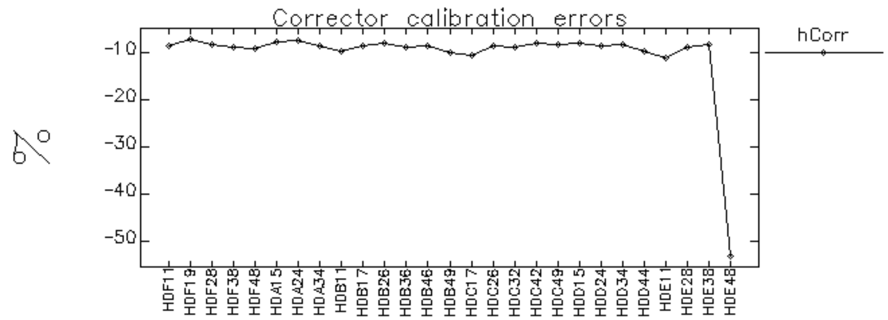
After the fit: 50 μm

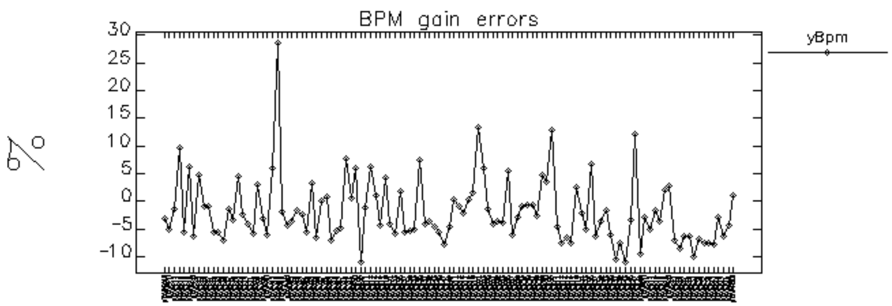


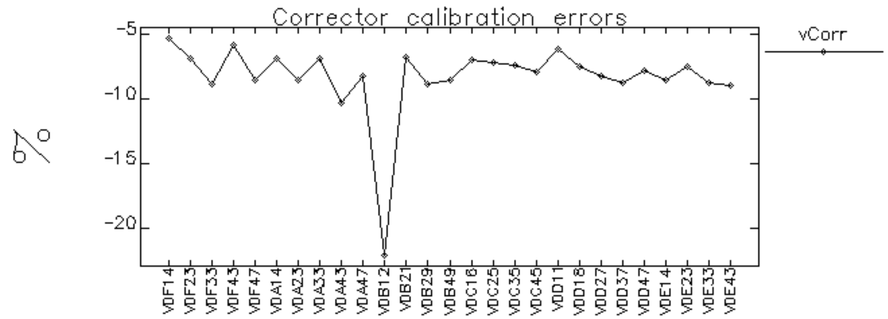
Rms difference for each BPM before and after the fit:

BPM and corrector errors:









Conclusions

- We build a model of Tevatron optics
  - It is based on (1) the differential orbit measurements and (2) the limited number of beta-function measurements in quads obtained by tune changes due to quad strength change
  - The model includes actual power supply currents
  - The results of magnetic measurements were fudged to match the model predictions and the measurements
- The model has been used to correct Tevatron optics and X-Y coupling. That allowed us
  - To decrease the emittance growth due to optics mismatch and coupling at injection (~10-15%)
  - To decrease beta-functions in IPs from ~45 cm to the design values of 35 cm

  These optics corrections contributed into collider luminosity growth of ~20-30%

- Presently, the accuracy of the model is limited by poor accuracy of BPM data and inefficient data processing. We are carrying out the following actions to improve accuracy of the model
  - Upgrade of BPM electronics will boost BPM accuracy from ~150 μm to 20 μm rms and will allow to acquire turn-by-turn data for all BPMs
  - Improvements in data analysis will make data processing faster and more accurate
  - Using turn by-turn data will further improve accuracy of the measurements and will allow to measure non-linearities of the lattice
- We see some effects of non-linearities in the model for uniform distribution of non-linearities in the model
- Realistic machine model (the same as the machine) will be much more sensitive to non-linearities for 3 mm orbit excitation